Optical Observations of Core-Collapse Supernovae

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Abstract. I present an overview of optical observations (mostly spectra) of Type II, Ib, and Ic supernovae (SNe). SNe II are defined by the presence of hydrogen, and exhibit a very wide variety of properties. SNe II-L tend to show evidence of late-time interaction with circumstellar material. SNe IIn are distinguished by relatively narrow emission lines with little or no P-Cygni absorption component and (quite often) slowly declining light curves; they probably have unusually dense circumstellar gas with which the ejecta interact. Some SNe IIn, however, might not be genuine SNe, but rather are "impostors" — specifically, super-outbursts of luminous blue variables. SNe Ib do not exhibit the deep 6150 Å absorption characteristic of "classical" SNe Ia; instead, their early-time spectra have He I absorption lines. SNe Ic appear similar to SNe Ib, but lack the helium lines as well. Spectra of SNe IIb initially exhibit hydrogen, yet gradually evolve to resemble those of SNe Ib; their progenitors seem to contain only a low-mass skin of hydrogen. Spectropolarimetry thus far indicates large asymmetries in the ejecta of SNe IIn, but much smaller ones in SNe II-P. As one peers deeper into the ejecta of core-collapse SNe, the asymmetry (indicated by the amount of polarization) seems to increase. There is intriguing, but inconclusive, evidence that some peculiar SNe IIn might be associated with gamma-ray bursts. The rates of different kinds of SNe as a function of Hubble type are still relatively poorly known, although there are good prospects for future improvement.

INTRODUCTION

Supernovae (SNe) occur in several spectroscopically distinct varieties; see reference [1], for example. Type I SNe are defined by the absence of obvious hydrogen in their optical spectra, except for possible contamination from superposed H II regions. SNe II all prominently exhibit hydrogen in their spectra, yet the strength and profile of the Hα line vary widely among these objects.

The early-time ($t \approx 1$ week past maximum brightness) spectra of SNe are illustrated in Figure 1. [Unless otherwise noted, the optical spectra illustrated here were obtained by my group, primarily with the 3-m Shane reflector at Lick Observatory. When referring to phase of evolution, the variables t and τ denote time since *maximum brightness* (usually in the B passband) and time since *explosion*, respectively.] The lines are broad due to the high velocities of the ejecta, and most of

them have P-Cygni profiles formed by resonant scattering above the photosphere. SNe Ia are characterized by a deep absorption trough around 6150 Å produced by blueshifted Si II λ6355. Members of the Ib and Ic subclasses do not show this line. The presence of moderately strong optical He I lines, especially He I λ5876, distinguishes SNe Ib from SNe Ic.

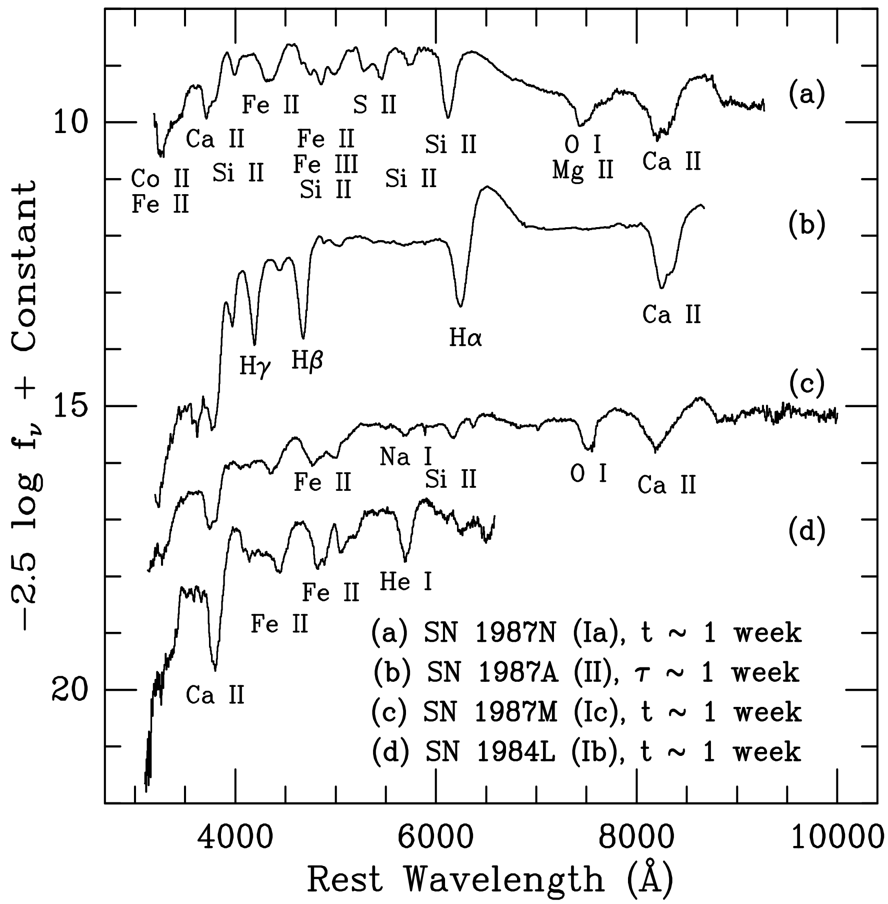

Figure 1: Early-time spectra of SNe, showing the main subtypes.

The late-time ($t \gtrsim 4$ months) optical spectra of SNe provide additional constraints on the classification scheme (Figure 2). SNe Ia show blends of dozens of Fe emission lines, mixed with some Co lines. SNe Ib and Ic, on the other hand, have relatively unblended emission lines of intermediate-mass elements such as O and Ca. At this phase, SNe II are dominated by the strong Hα emission line; in other respects, most of them spectroscopically resemble SNe Ib and Ic, but with narrower emission lines. The late-time spectra of SNe II show substantial heterogeneity, as do the early-time spectra.

To a first approximation, the light curves of SNe I are all broadly similar [2]. SNe Ib usually have slower decline rates than SNe Ic; however, SNe Ic may come in "slow" and "fast" varieties [3,4]. The light curves of SNe II exhibit much dispersion [5], though it is useful to subdivide the majority of them into two relatively distinct

subclasses [6,7]. The light curves of SNe II-L ("linear") generally resemble those of SNe I, with a steep decline after maximum brightness followed by a slower exponential tail. In contrast, SNe II-P ("plateau") remain within ~ 1 mag of maximum brightness for an extended period. The light curve of SN 1987A, albeit atypical, was generically related to those of SNe II-P.

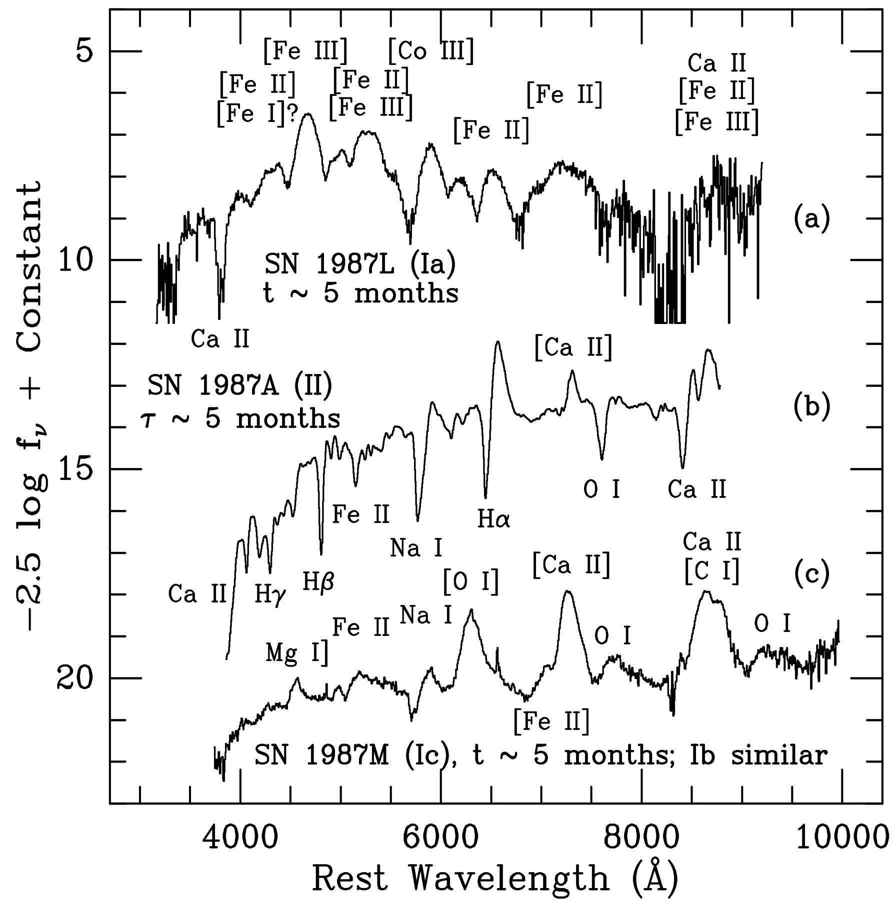

Figure 2: Late-time spectra of SNe. At even later phases, SN 1987A was dominated by strong emission lines of Hα, [O I], [Ca II], and the Ca II near-infrared triplet.

The locations at which SNe occur provide important clues to their nature, and to the mass of their progenitor stars. SNe II, Ib, and Ic have *never* been seen in elliptical galaxies, and rarely if ever in S0 galaxies. They are generally in or near spiral arms and H II regions [8], implying that their progenitors must have started their lives as massive stars ($\gtrsim 10\ M_\odot$). The progenitors of SNe II are thought to suffer core collapse and subsequently "rebound" with help from neutrinos [9,10], leaving a neutron star or perhaps in some cases a black hole [11]. Most workers now believe that SNe Ib/Ic are produced by the same mechanism as SNe II, except that the progenitors were stripped of their hydrogen (SN Ib) and possibly helium (SN Ic) envelopes prior to exploding, either via mass transfer to companion stars [12,13] or through winds (e.g., [14,15]). White dwarf models have been discussed [16] but are unlikely.

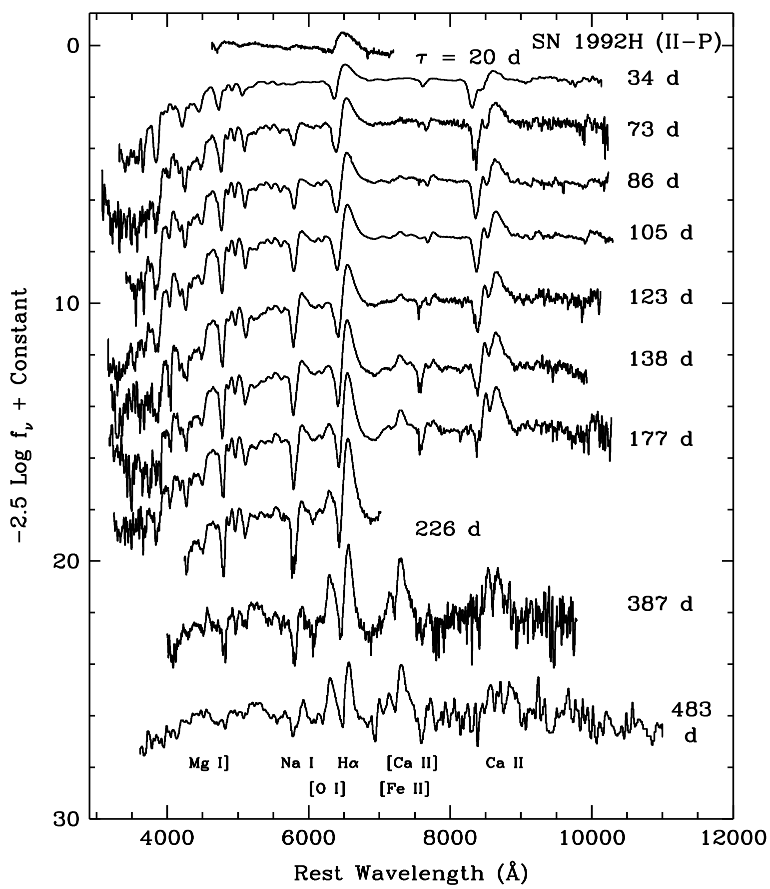

Figure 3: Montage of spectra of SN 1992H in NGC 5377. Epochs (days) are given relative to the estimated time of explosion, February 8, 1992.

SUBCLASSES OF TYPE II SUPERNOVAE

Most SNe II-P seem to have a relatively well-defined spectral development, as shown in Figure 3 for SN 1992H (see also reference [17]). At early times the spectrum is nearly featureless and very blue, indicating a high color temperature ($\gtrsim$ 10,000 K). He I λ5876 with a P-Cygni profile is sometimes visible. The temperature rapidly decreases with time, reaching $\sim$ 5000 K after a few weeks, as expected from the adiabatic expansion and associated cooling of the ejecta. It remains roughly constant at this value during the plateau (the photospheric phase), while the hydrogen recombination wave moves through the massive ($\sim 10\ M_{\odot}$) hydrogen ejecta and releases the energy deposited by the shock. At this stage strong Balmer lines and Ca II H&K with well-developed P-Cygni profiles appear, as do weaker lines of Fe II, Sc II, and other iron-group elements. The spectrum gradually takes on a nebular appearance as the light curve drops to the late-time tail; the continuum

fades, but Hα becomes very strong, and prominent emission lines of [O I], [Ca II], and Ca II also appear.

Few SNe II-L have been observed in as much detail as SNe II-P. Figure 4 shows the spectral development of SN 1979C [18], an unusually luminous member of this subclass. Near maximum brightness the spectrum is very blue and almost featureless, with a slight hint of Hα emission. A week later, Hα emission is more easily discernible, and low-contrast P-Cygni profiles of Na I, Hβ, and Fe II have appeared. By $t \approx 1$ month, the Hα emission line is very strong but still devoid of an absorption component, while the other features clearly have P-Cygni profiles. Strong, broad Hα emission dominates the spectrum at $t \approx 7$ months, and [O I] $\lambda\lambda$6300, 6364 emission is also present. Several authors [19–21] have speculated that the absence of Hα absorption spectroscopically differentiates SNe II-L from SNe II-P, but the small size of the sample of well-observed objects precluded definitive conclusions.

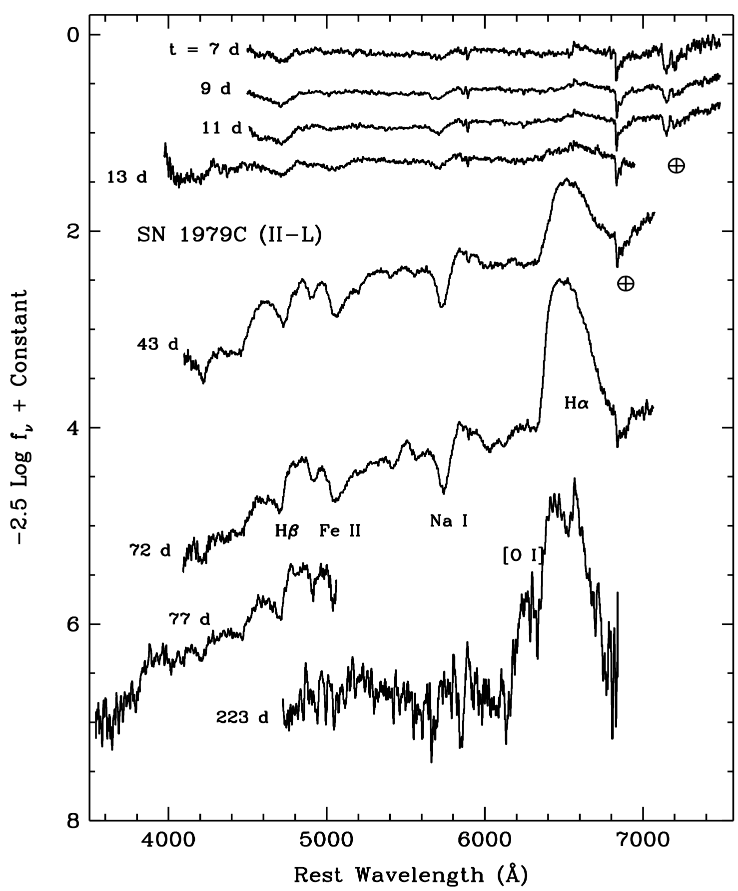

Figure 4: Montage of spectra of SN 1979C in NGC 4321, from reference [18]; reproduced with permission. Epochs (days) are given relative to the date of maximum brightness, April 15, 1979.

The progenitors of SNe II-L are generally believed to have relatively low-mass hydrogen envelopes (a few $M_\odot$); otherwise, they would exhibit distinct plateaus, as do SNe II-P. On the other hand, they may have more circumstellar gas than do SNe II-P, and this could give rise to the emission-line dominated spectra. They are often radio sources [22]; moreover, the ultraviolet excess (at $\lambda \lesssim 1600$ Å) seen in SNe 1979C and 1980K may be produced by inverse Compton scattering of photospheric radiation by high-speed electrons in shock-heated ($T \approx 10^9$ K) circumstellar material [23,24]. Finally, the light curves of some SNe II-L reveal an extra source of energy: after declining exponentially for several years, the Hα flux of SN 1980K reached a steady level, showing little if any decline thereafter [25,26]. The excess almost certainly comes from the kinetic energy of the ejecta being thermalized and radiated due to an interaction with circumstellar matter [27,28].

The very late-time optical recovery of SNe 1979C and 1980K [26,29,30] and other SNe II-L supports the idea of ejecta interacting with circumstellar material. The spectra consist of a few strong, broad emission lines such as Hα, [O I] $\lambda\lambda$6300, 6364, and [O III] $\lambda\lambda$4959, 5007. A *Hubble Space Telescope (HST)* ultraviolet spectrum of SN 1979C reveals some prominent, double-peaked emission lines with the blue peak substantially stronger than the red, suggesting dust extinction within the expanding ejecta [30]. The data show general agreement with the emission lines expected from circumstellar interaction [31], but the specific models that are available show several differences with the observations. For example, we find higher electron densities (10^5 to 10^7 cm^{-3}), resulting in stronger collisional de-excitation than assumed in the models. These differences can be used to further constrain the nature of the progenitor star. Note that based on photometry of the stellar populations in the environment of SN 1979C (from *HST* images), the progenitor of the SN was at most 10 million years years old, so its initial mass was probably 17–18 $M_\odot$ [32].

During the past decade, there has been the gradual emergence of a new, distinct subclass of SNe II [20,33,34,28] whose ejecta are believed to be *strongly* interacting with dense circumstellar gas, even at early times (unlike SNe II-L). The derived mass-loss rates for the progenitors can exceed $10^{-4} M_\odot$ yr^{-1} [35]. In these objects, the broad absorption components of all lines are weak or absent throughout their evolution. Instead, their spectra are dominated by strong emission lines, most notably Hα, having a complex but relatively narrow profile. Although the details differ among objects, Hα typically exhibits a very narrow component (FWHM $\lesssim$ 200 km s^{-1}) superposed on a base of intermediate width (FWHM $\approx$ 1000–2000 km s^{-1}; sometimes a very broad component (FWHM $\approx$ 5000–10,000 km s^{-1}) is also present. This subclass was christened "Type IIn" [34], the "n" denoting "narrow" to emphasize the presence of the intermediate-width or very narrow emission components. Representative spectra of five SNe IIn are shown in Figure 5, with two epochs for SN 1994Y.

The early-time continua of SNe IIn tend to be bluer than normal. Occasionally He I emission lines are present in the first few spectra (e.g., SN 1994Y in Figure 5). Very narrow Balmer absorption lines are visible in the early-time spectra of some of

these objects, often with corresponding Fe II, Ca II, O I, or Na I absorption as well (e.g., SNe 1994W and 1994ak in Figure 5). Some of them are unusually luminous at maximum brightness, and they generally fade quite slowly, at least at early times. The equivalent width of the intermediate Hα component can grow to astoundingly high values at late times. The great diversity in the observed characteristics of SNe IIn provides clues to the various degrees and forms of mass loss late in the lives of massive stars.

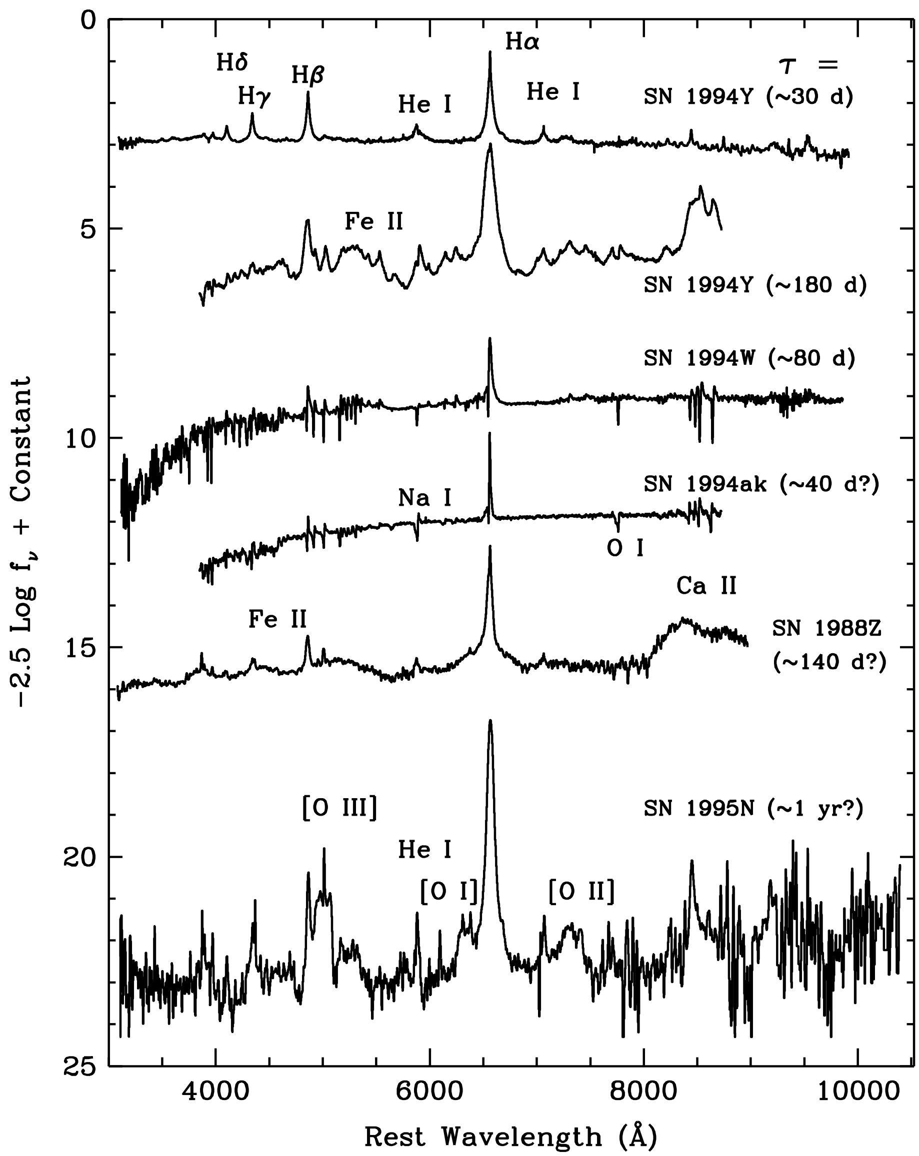

Figure 5: Montage of spectra of SNe IIn. Epochs are given relative to the estimated dates of explosion.

TYPE II SUPERNOVA IMPOSTORS?

The peculiar SN IIn 1961V ("Type V" according to Zwicky [36]) had probably the most bizarre light curve ever recorded. (SN 1954J, also known as "Variable 12" in NGC 2403, was similar [37].) Its progenitor was a very luminous star, visible in many photographs of the host galaxy (NGC 1058) prior to the explosion. Perhaps SN 1961V was not a genuine supernova (defined to be the violent destruction of a star at the end of its life), but rather the super-outburst of a luminous blue variable such as η Carinae [38,39].

A related object may have been SN IIn 1997bs, the first SN discovered in the Lick Observatory Supernova Search (LOSS, described later in this review). Its spectrum was peculiar (Figure 6), consisting of narrow Balmer and Fe II emission lines superposed on a featureless continuum. Its progenitor was discovered in an *HST* archival image of the host galaxy [40]. It is a very luminous star ($M_V \approx -7.4$ mag), and it didn't brighten as much as expected for a SN explosion ($M_V \approx -13$ at maximum). These data suggest that SN 1997bs may have been like SN 1961V — that is, a supernova impostor. The real test will be whether the star is still visible in future *HST* images obtained years after the outburst.

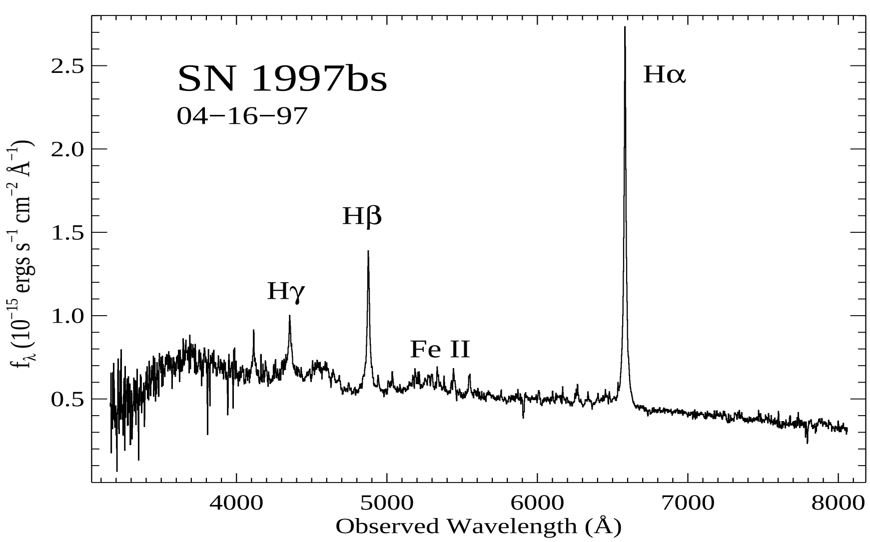

Figure 6: Spectrum of SN 1997bs, obtained on April 16, 1997 UT.

TYPE IB AND IC SUPERNOVAE

In the 1960s, Bertola and collaborators [41,42] recognized that not all SNe I are of the "classical" variety (now known as SNe Ia) with a strong absorption trough

near 6150 Å. By the mid-1980s these objects came to be known as SNe Ib [43], and He I lines were identified in their early-time spectra [44]. Gradually it became clear that SNe Ib constitute a heterogeneous subclass, with substantial variations in the observed He I strengths in spectra obtained around maximum brightness. Wheeler & Harkness ([45]; see also [44]) suggested that SNe Ib should actually be divided into two separate categories: SNe Ib are those showing strong He I absorption lines (especially He I λ5876) in their early-time photospheric spectra, while SNe Ic are those in which He I is not easily discernible. However, they modeled SNe Ic in the same physical way as SNe Ib [46], but with different relative concentrations of He and O in the envelope.

A large, comprehensive study of SNe Ib and SNe Ic was recently completed by my group [47]. The relative depths of the helium absorption lines in the spectra of the SNe Ib appear to provide a measurement of the temporal evolution of the supernova, with He I λ5876 and He I λ7065 growing in strength relative to He I λ6678 over time. Some SNe Ic show evidence for weak He I absorption, but most do not. Aside from the presence or absence of the helium lines, there are other spectroscopic differences between SNe Ib and SNe Ic. On average, the O I λ7774 line is stronger in SNe Ic than in SNe Ib. In addition, the SNe Ic have distinctly broader emission lines at late times, indicating either a consistently larger explosion energy and/or a lower envelope mass for SNe Ic than for SNe Ib. These results are consistent with the idea that the progenitors of SNe Ic are massive stars that have lost more of their envelope (i.e., much of the helium layer) than the progenitors of SNe Ib. The general hypothesis that SNe Ib/Ic have "stripped" progenitors is greatly supported by the discovery of links between SNe II and SNe Ib/Ic, as I discuss next.

LINKS BETWEEN TYPE II AND TYPE IB/IC SUPERNOVAE

Filippenko [48] presented the case of SN 1987K, which appeared to be a link between SNe II and SNe Ib. Near maximum brightness, it was undoubtedly a SN II, but with rather weak photospheric Balmer and Ca II lines. Many months after maximum brightness, its spectrum was essentially that of a SN Ib. The simplest interpretation is that SN 1987K had a meager hydrogen atmosphere at the time it exploded; it would naturally masquerade as a SN II for a while, and as the expanding ejecta thinned out the spectrum would become dominated by emission from deeper and denser layers. The progenitor was probably a star that, prior to exploding via iron core collapse, lost almost all of its hydrogen envelope either through mass transfer onto a companion or as a result of stellar winds. Such SNe were dubbed "SNe IIb" by Woosley et al. [49], who had proposed a similar preliminary model for SN 1987A before it was known to have a massive hydrogen envelope.

The data for SN 1987K (especially its light curve) were rather sparse, making

it difficult to model in detail. Fortunately, the Type II SN 1993Jin NGC 3031 (M81) came to the rescue, and was studied in greater detail than any supernova since SN 1987A [50]. Its light curves [51] and spectra [52–55] amply supported the hypothesis that the progenitor of SN 1993J probably had a low-mass (0.1–0.6 $M_{\odot}$) hydrogen envelope above a $\sim 4\ M_{\odot}$ He core [56–58]. Figure 7 shows several early-time spectra of SN 1993J, showing the emergence of He I features typical of SNe Ib. Considerably later (Figure 8), the Hα emission nearly disappeared, and the spectral resemblance to SNe Ib was strong. The general consensus is that its initial mass was $\sim 15\ M_{\odot}$. A star of such low mass cannot shed nearly its entire hydrogen envelope without the assistance of a companion star. Thus, the progenitor of SN 1993J probably lost most of its hydrogen through mass transfer to a bound companion 3–20 AU away. In addition, part of the gas may have been lost from the system. Had the progenitor lost essentially *all* of its hydrogen prior to exploding, it would have had the optical characteristics of SNe Ib. There is now little doubt that most SNe Ib, and probably SNe Ic as well, result from core collapse in stripped, massive stars, rather than from the thermonuclear runaway of white dwarfs.

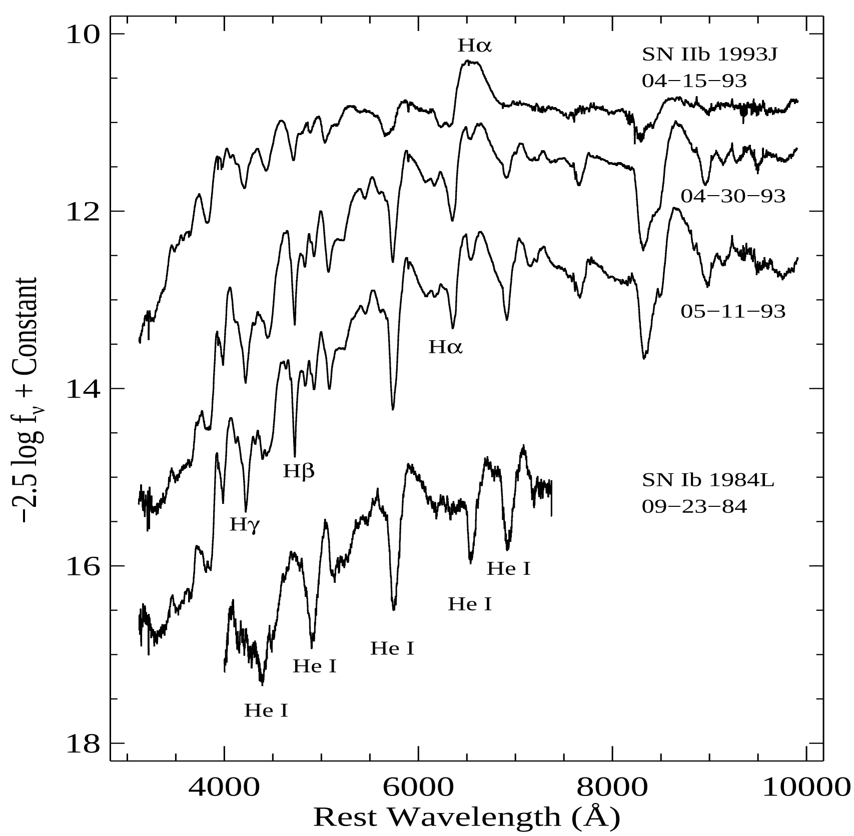

Figure 7: Early-time spectral evolution of SN 1993J. A comparison with the Type Ib SN 1984L is shown at bottom, demonstrating the presence of He I lines in SN 1993J. The explosion date was March 27.5, 1993.

SN 1993J held several more surprises. Observations at radio [59] and X-ray [60] wavelengths revealed that the ejecta are interacting with relatively dense circumstellar material [61], probably ejected from the system during the course of its pre-SN evolution. Optical evidence for this interaction also began emerging at $\tau \gtrsim 10$ months: the Hα emission line grew in relative prominence, and by $\tau \approx 14$ months it had become the dominant line in the spectrum [53,62,63], consistent with models [31]. Its profile was very broad (FWHM $\approx$ 17,000 km s^{-1}; Figure 8) and had a relatively flat top, but with prominent peaks and valleys whose likely origin is Rayleigh-Taylor instabilities in the cool, dense shell of gas behind the reverse shock [64]. Radio VLBI measurements show that the ejecta are circularly symmetric, but with significant emission asymmetries [65], possibly consistent with the asymmetric Hα profile seen in some of the spectra [53].

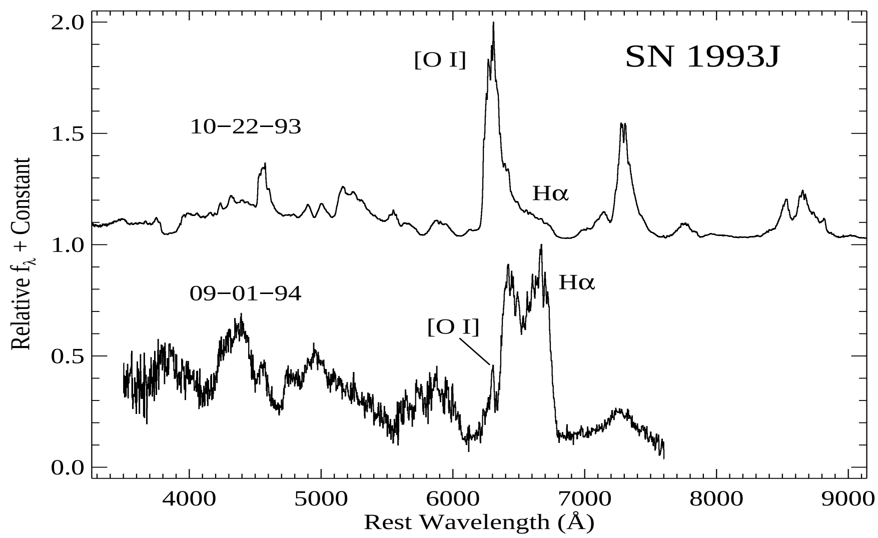

Figure 8: In the *top* spectrum, which shows SN 1993J about 7 months after the explosion, Hα emission is very weak; the resemblance to spectra of SNe Ib is striking. A year later (*bottom*), however, Hα was once again the dominant feature in the spectrum (which was scaled for display purposes).

SPECTROPOLARIMETRY OF SUPERNOVAE

Spectropolarimetry of SNe can be used to probe their geometry. The basic question is whether SNe are round, and the idea is simple: A hot young SN atmosphere is dominated by electron scattering, which by its nature is highly polarizing. For an unresolved, spherical source, however, the directional components of the electric vectors cancel exactly, yielding zero net linear polarization. Conversely, if the source is aspherical, incomplete cancellation occurs and a net linear polarization results,

with typical continuum polarizations of $\sim 1\%$ expected for objects with moderate ($\sim 20\%$) asphericity (e.g., [66]), although the exact amount of polarization observed is also sensitive to the viewing angle. Spectropolarimetry is important for a full understanding of the physics of SN explosions and can also provide information on the circumstellar environment of SNe.

My group obtained spectropolarimetry of one object from each of the major SN types and subtypes [67], generally with the Keck-II 10-m telescope (but in a few important cases with the Lick 3-m Shane reflector). Most of the objects exhibit a change in both the magnitude and direction of the polarization across strong lines, especially the absorption troughs of the strongest P-Cygni lines. This may result from global asymmetry of the electron-scattering atmosphere and/or the underlying continuum region [68,66].

We have studied SN IIn 1998S in some detail [69] (see also [70]); its optical spectrum is dominated by strong, multi-component emission lines, thought to be produced by an intense interaction between the supernova and its dense circumstellar environment. We combined our early-time (3 days after discovery) spectropolarimetric observation with total flux spectra spanning nearly 500 days. We measure an intrinsic continuum polarization of $p \approx 3\%$ (one of the highest yet found for a SN), suggesting a global asphericity of $\gtrsim 45\%$ from the models of Höflich [66]. The line profiles favor a ring-like geometry for the circumstellar gas, generically similar to what is seen directly in SN 1987A, although much denser and closer to the progenitor in SN 1998S.

We also found that one month after exploding, the Type IIb SN 1993J had a polarized flux spectrum resembling spectra of SNe Ib, with prominent He I lines [71]. The data are consistent with models in which the polarization is produced by an asymmetric He core configuration of material. It is interesting that the percent polarization may increase with decreasing envelope mass, along the sequence Type II, IIb, Ib, and Ic [72,70,73], suggesting that asymmetries in massive stars become more pronounced as one probes deeper into the core.

SN 1999em, an extremely bright ($m_V \approx 13.5$) SN II-P, provided the rare opportunity to study the geometry of a "normal" core-collapse event at multiple epochs [74]. We obtained spectropolarimetry at 3 plateau-phase epochs, and then one final epoch long after it had dropped off the plateau (Fig. 9). A very low but temporally increasing polarization level suggests a substantially spherical geometry at early times that becomes more aspherical at late times as ever-deeper layers of the ejecta are revealed. We speculate that the thick hydrogen envelope intact at the time of explosion in SNe II-P might serve to dampen the effects of an intrinsically aspherical explosion. The increase in asphericity seen at later times is consistent with the trend identified above among stripped-envelope core-collapse SNe: the deeper we peer, the more evidence we find for asphericity. The natural conclusion that it is *explosion* asymmetry that is responsible for the polarization has fueled the idea that some core-collapse SNe produce gamma-ray bursts (GRB; e.g., [75]) through the action of a jet of material aimed fortuitously at the observer, the result of a "bipolar," jet-induced, SN explosion [76,72].

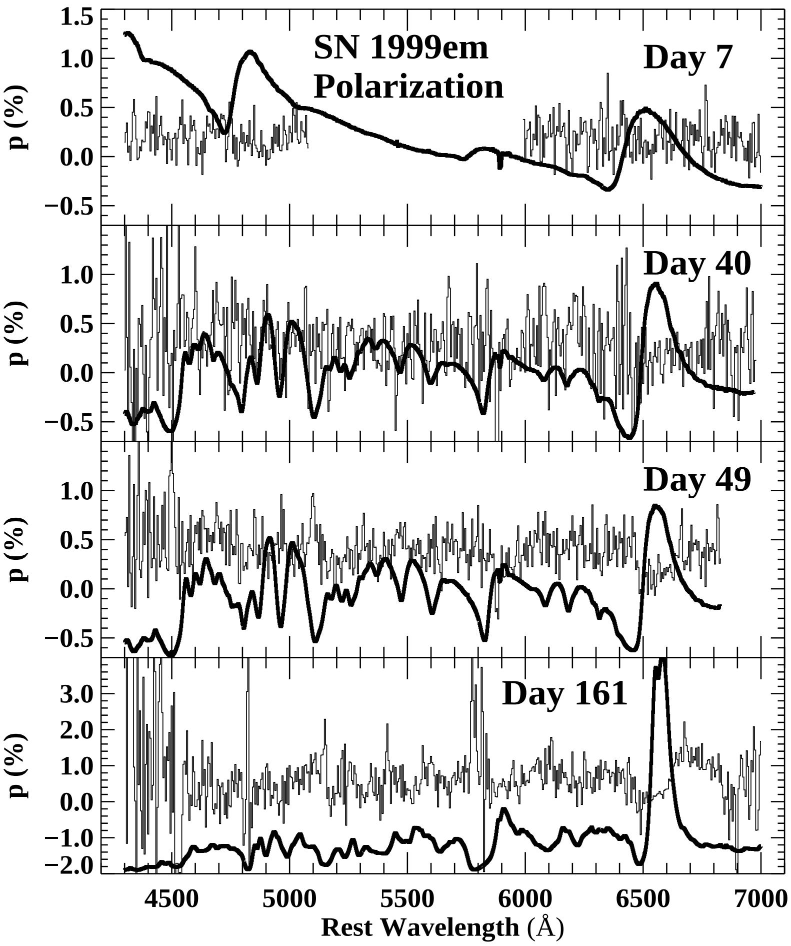

Figure 9: Montage of the observed optical polarization of SN 1999em, with arbitrarily scaled total flux spectra *(thick lines)* overplotted for comparison of features. The polarization spectra are binned 5 Å bin^{-1} to improve the S/N ratio. See reference [73] for details.

SUPERNOVAE ASSOCIATED WITH GAMMA-RAY BURSTS?

At least a small fraction of gamma-ray bursts (GRBs) may be associated with nearby SNe. Probably the most compelling example thus far is that of SN 1998bw and GRB 980425 (e.g., [77–80]), which were temporally and spatially coincident. SN 1998bw was, in many ways, an extraordinary SN; it was very luminous at optical and radio wavelengths, and it showed evidence for relativistic outflow. Its bizarre optical spectrum is often classified as that of a SN Ic, but the object should be

called a "peculiar SN Ic" if not a subclass of its own; the spectrum was distinctly different from that of a normal SN Ic.

Models suggest that SNe associated with GRBs are highly asymmetric; thus, spectropolarimetry should provide some useful tests. In particular, perhaps objects such as SN 1998S, mentioned above, would have been seen as GRBs had their rotation axis been pointed in our direction. That of SN 1998S was almost certainly *not* aligned with us [69]; both the spectropolarimetry and the appearance of double-peaked Hα emission suggest an inclined view, rather than pole-on.

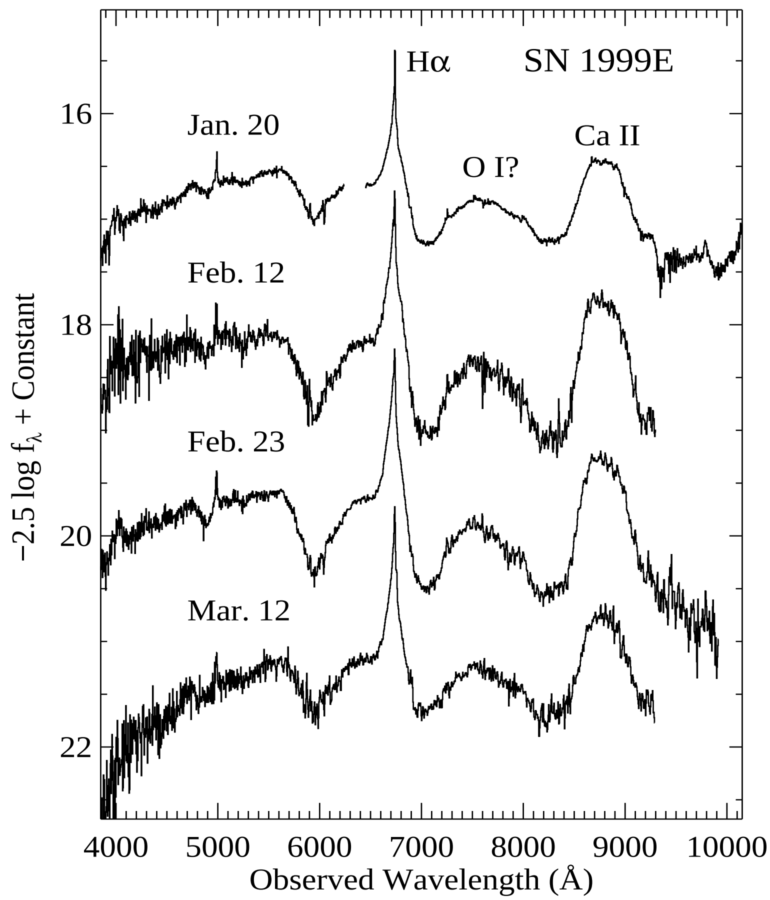

Figure 10: Spectral evolution of SN 1999E, which may have been associated with GRB 980910.

The case of GRB 970514 and the very luminous SN IIn 1997cy is also interesting [81,82]; there is a reasonable possibility that the two objects were associated. The optical spectrum of SN 1997cy was highly unusual, and bore some resemblance to that of SN 1998bw, though there were some differences as well. SN 1999E, which might be linked with GRB 980910 but with large uncertainties [83], also had an optical spectrum similar to that of SN 1997cy [84,85]; see Figure 10. The undulations are very broad, indicating high ejection velocities. Besides Hα, secure

line identifications are difficult, though some of the emission features seem to be associated with oxygen and calcium. Perhaps SN 1999E was produced by the highly asymmetric collapse of a carbon-oxygen core.

SUPERNOVA RATES

I conclude with a brief summary of supernova rates. The derived rates of various types of SNe as a function of Hubble type are still quite uncertain; no single search has found a sufficiently large sample of SNe, and combining different searches can be misleading due to differences in the dominant selection effects. Probably the best existing determination of supernova rates is that of Capellaro et al. [86], who combined the results of five searches while being attentive to various selection effects. Four of the searches had been done with photographic plates, while the fifth was a visual search by the Rev. Robert Evans. Given that photographic searches can be rather insensitive to SNe near the central regions of galaxies, and that the Evans visual search did not go very deep, we must avoid the temptation to take the overall results (see table below) too literally. Nevertheless, they can be used as a rough guideline.

SNu $[\#(100\ \mathrm{yr})^{-1}(10^{10} L_{\odot}^{B})^{-1}]$

Galaxy type	Ia	Ib/c	II	All
E-S0	0.18 ± 0.06	< 0.01	< 0.02	0.18 ± 0.06
S0a-Sb	0.18 ± 0.07	0.11 ± 0.06	0.42 ± 0.19	0.72 ± 0.21
Sbc-Sd	0.21 ± 0.08	0.14 ± 0.07	0.86 ± 0.35	1.21 ± 0.37
Others*	0.40 ± 0.16	0.22 ± 0.16	0.65 ± 0.39	1.26 ± 0.45
All	0.20 ± 0.06	0.08 ± 0.04	0.40 ± 0.19	0.68 ± 0.20

Note: $H_0 = 75$ km s^{-1} Mpc^{-1}; scale by $(H_0/75)^2$.
*Others include Sm, Irr, Pec.

My group is trying to remedy the situation by conducting a long-term search for nearby SNe (with redshifts generally less than 5000 km s^{-1}) in a uniform manner [87,88]. Special emphasis is placed on finding them well before maximum brightness. We are using the Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory, a fully robotic 0.75-m reflector equipped with a CCD imaging camera. Its telescope control system checks the weather, opens the dome, points to the desired objects, finds and acquires guide stars (only for long integrations), exposes, stores the data, and manipulates the data without human intervention. There is a filter wheel with 20 slots, including UBVRI. Five-minute guided exposures yield $R \approx 20$ mag.

A limit of about 19 mag (4σ) is reached in the 25-second unfiltered, unguided exposures of our Lick Observatory Supernova Search (LOSS). We observe up to 1200 galaxies per night, and try to cycle back to the same galaxies after 3–4 nights. Our

software automatically subtracts new images from old ones and identifies supernova candidates that are subsequently examined by undergraduate research assistants. LOSS found 20 SNe in 1998, 40 in 1999, and 36 in 2000, making KAIT the world's most successful search engine for nearby SNe. (Note that we found SN 2000A and SN 2001A — and hence the first supernova of the new millennium regardless of one's definition of the turn of the millennium!) After a few more years, we hope to have found enough SNe to provide a meaningful update on the supernova rates given above.

Multi-filter follow-up photometry is conducted of the most important SNe, and all objects are monitored in unfiltered mode. A Web page describing LOSS is at http://astro.berkeley.edu/∼bait/kait.html . As a byproduct of LOSS, we also find novae in the Local Group, comets, asteroids, and cataclysmic variables.

ACKNOWLEDGMENTS

My recent research on SNe has been financed by the NSF, most recently through grant AST-9987438, as well as by NASA grants GO-7821, GO-8243, GO-8648, AR-6371, and AR-8006 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA Contract NAS5-26555. Additional funding was provided by NASA/Chandra grant GO-0-1009C. KAIT and its associated science have been made possible with funding or donations from NSF, NASA, the Sylvia and Jim Katzman Foundation, Sun Microsystems Inc., Lick Observatory, the Hewlett-Packard Company, Photometrics Ltd., AutoScope Corporation, and the University of California. This paper was written while I was supported by a Guggenheim Fellowship. I am grateful to the students and postdocs who have worked with me on SNe over the past 15 years for their assistance and discussions.

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